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Ozone and temperature decadal responses to solar variability in the mesosphere and lower thermosphere, based on measurements from SABER on TIMED

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Abstract. We have derived ozone and temperature responses to solar variability over a solar cycle, from June 2002 through June 2014, 50 to 100 km, 48° S to 48° N, based on data from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the Thermosphere-Ionosphere-Mesosphere-Energetics and Dynamics (TIMED) satellite. Results with this extent of coverage in the mesosphere and lower thermosphere have not been available previously. A multiple regression is applied to obtain responses as a function of the solar 10.7 cm flux (solar flux units, sfu). Positive responses mean that they are larger at solar maximum than at solar minimum of the solar cycle. From ∼ 80 to 100 km, both ozone and temperature responses are positive for all latitudes and are larger than those at lower altitudes. From ∼ 80 to 100 km, ozone responses can exceed 10 % $(100\,\mathrm{sfu})^{-1}$, and temperature responses can approach 4 °K. From 50 to ∼ 80 km, the ozone responses at low latitudes (∼ ±35°) are mostly negative and can approach ∼ negative 3 % $(100\,\mathrm{sfu})^{-1}$. However, they are mostly positive at midlatitudes in this region and can approach ∼ 2 % $(100\,\mathrm{sfu})^{-1}$. In contrast to ozone, from ∼ 50 to 80 km, the temperature responses at low latitudes remain positive, with values up to ∼ 2.5 K $(100\,\mathrm{sfu})^{-1}$, but are weakly negative at midlatitudes. Consequently, there is a systematic and robust relation between the phases of the ozone and temperature responses. They are positively correlated (in phase) from ∼ 80 to 100 km for all latitudes and negatively correlated (out of phase) from ∼ 50 to 80 km, also for all latitudes. The negative correlation from 50 to 80 km is maintained even though the ozone and temperature responses can change signs as a function of altitude and latitude, because the corresponding temperature responses change signs in step with ozone. This is consistent with the idea that dynamics have the larger influence between ∼ 80 and 100 km, while photochemistry is more in control from ∼ 50 to 75 km. The correlation coefficients between the solar 10.7 cm flux and the ozone and temperature themselves from 2012 to 2014 are positive (negative) in regions where the responses are positive (negative). This supports our results since the correlations are independent of the multiple regression used to derive the responses. We also compare with previous results.

Keywords. Meteorology and atmospheric dynamics (climatology)

1 Introduction

An understanding of the response of atmospheric ozone and temperature to solar variability over a solar cycle (∼ 11 years) is both interesting for scientific reasons and important for practical reasons. In recent years, advances in theoretical studies such as 3-D coupled chemistry–climate models, in conjunction with empirical results, have helped to increase our understanding considerably. However, further studies are still needed (e.g., see Austin et al., 2008; Beig et al., 2012) to understand the dynamics, photochemistry, and energy transfer throughout the atmosphere. Measurements are challenging due to the need for synoptic, global-scale measurements over one or more solar cycles.

In the following, we focus on empirical results of ozone and temperature responses to solar variability over a solar cycle in the mesosphere and lower thermosphere (50–100 km). In this region, there is a relative dearth of measurements compared to the stratosphere. Measurements are made by satellite-borne, rocket-borne, and ground-based instruments. However, operational satellites, which are meant to provide measurements over the longer term of decades or more, are concentrated at lower altitudes in the stratosphere, and ground-based and rocket-borne measurements do not have the spatial coverage.

Here we provide new empirical results for zonal mean ozone and temperature responses to solar variability from June 2002 through June 2014, 50 to 100 km, and 48° S to 48° N latitude, based on measurements from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument (Russell et al., 1999) on the Thermosphere-Ionosphere-Mesosphere-Energetics and Dynamics (TIMED) satellite. The data are unique in the breadth of their information content, being made over the globe from 20 to 100 km, over 24 h in local solar time (LST), since the beginning of 2002. Measurements of ozone and temperature taken together, with this detailed space–time coverage, from one instrument, have not been available previously. We plan to present corresponding results for the stratosphere in a subsequent article.

Other satellite data that were used in previous studies provided measurements at only one or two fixed local times. SABER measures over the 24 h of local time, thereby providing the opportunity to derive the variations of ozone and temperature as a function local time. This also makes it straightforward to compare directly with 3-D models, whose zonal means are a consistent average of variations over longitude and local time (Austin et al., 2008).

SABER also provides measurements of ozone and temperature that are co-located in space–time. This will help significantly in the interpretation of results. SABER is still currently operational and hopefully will provide longer measurements in time.

Previous empirical results, based on a combination of satellite, ground-based, and rocket-borne measurements, do cover a larger latitude range than we present here, but there are gaps in overall altitude and latitude coverage, compared to SABER. The latitude and altitude resolutions of 4° and 2.5 km of the results are also an advantage compared to other measurements.

Data from the Halogen Occultation Experiment (HALOE) on the Upper Atmosphere Research Satellite (UARS) contain the majority of the information provided by SABER measurements, although the measurements are made only at sunset and sunrise. Nevertheless, we will see below that comparisons based on HALOE data with our results are fruitful.

2 Data characteristics and analysis

SABER ozone and temperature measurements have been analyzed with success over the past decade. Using SABER data, we have derived ozone and temperature variations with periods from 1 day or less (diurnal variations) up to multiple years (semiannual oscillations (SAOs) and quasi-biennial oscillations, QBOs), and 1 decade or more (trends). See Huang et al. (2008a, 2010a, b, 2014). Studies by others using SABER temperature (diurnal tides) include Zhang et al. (2006) and Mukhtarov et al. (2009). Nath and Sridharan (2014) have also derived results of response to solar variability using SABER data at 10–15° latitude (see Sect. 4.2).

For both ozone and temperature, these studies show that, for variations that are deviations from a mean state (e.g., diurnal variations, tides, SAOs, QBOs, trends), SABER measurements are robust and precise. For example, zonal mean tidal temperatures can agree with other measurements to within $\sim 1\,^{\circ}$K (Huang et al., 2010a), and zonal mean ozone diurnal variations agree with other measurements to less than a few percent (Huang et al., 2010b). Deviations from a mean state also include variations such as trends and, what is relevant here, responses to solar variability. It is the systematic uncertainties (accuracy) that can be larger.

2.1 Data characteristics

The data are provided by the SABER project (version 2.0, level2A). They are interpolated to 4° latitude and 2.5 km altitude grids, after which zonal averages are taken for analysis.

A feature of SABER data is that, unlike other satellites, the orbital characteristics of TIMED are such that SABER samples over the 24 h of local time, which can be used to estimate diurnal variations of ozone and temperature (e.g., thermal tides). Variations with local time are especially important in the mesosphere and lower thermosphere, where the ozone and temperature diurnal amplitudes can be dominant. Even in the stratosphere, ozone and temperature diurnal variations may not be negligible (Huang et al. 2010a, b). A complication is that it takes SABER 60 days to sample over the 24 h of local time. Over this period, the variations with local time are embedded with the seasonal variations and need to be separated from them. The method we use estimates both the diurnal and mean variations (e.g., seasonal, semiannual, annual) together, by performing a least-squares fit of a two-dimensional Fourier series, where the independent variables are local time and day of year. The algorithm is discussed further in Huang et al. (2010a, b).

2.2 Data analysis

2.2.1 Estimation of variations with the solar cycle

The variations with solar activity, as represented by the 10.7 cm solar flux, are estimated in a similar manner as previously done by others, using a multiple regression analysis (e.g., Keckut et al, 2005; Soukharev and Hood, 2006; Bevington and Robinson, 1992) that includes solar activity, trends, seasonal, QBO, and local time terms, on monthly values.

Specifically, the estimates are found from a multiple regression (least-squares) analysis of the equation

$$M(t) = a + b \times t + d \times \mathrm{F107}(t) + c \times S(t) + l \times lst(t) + g \times \mathrm{QBO}(t), \qquad (1)$$

where t is time (months), $M(t)$ stands for the ozone mixing ratio or temperature measurements, a is a constant, b is the trend, d is the coefficient for solar activity (10.7 cm flux), c is the coefficient for the seasonal ($S(t)$) variations, l is the coefficient for local time (lst) variations, and g stands for the coefficient of the QBO. As is often done, the seasonal and local time variations are removed first, but we include them in Eq. (1) for completeness. The F107 stands for the solar 10.7 cm flux, which is commonly used as a measure of solar activity, and the values used here are monthly means provided by NOAA. This algorithm is applied to zonal mean monthly values of SABER data from June 2002 through June 2014 (as in Fig. 1), from 48° S to 48° N latitude, and from 20 to 100 km. The year 2002 was near solar maximum, the middle of solar cycle 23, and 2014 is some years into cycle 24, which began in $\sim$ 2008.

Eq. (1) has also been used by others and by us to estimate corresponding ozone and temperature trends (Huang et al., 2014).

2.2.2 Statistical and error considerations

Commonly, a criterion that is used to indicate if the estimated response to solar activity is statistically significant is that its magnitude be greater than 2σ ($\sim$95% confidence level), where σ is the uncertainty of the estimated response. However, in our case, the uncertainties (e.g., data variances) of the SABER data themselves, which are needed for obtaining the uncertainties in the responses to solar variability, are not available. In place of the data variances, we use the sum of squares of the residuals, normalized by the number of degrees of freedom of the fit, namely, the sample variance (Bevington and Robinson, 1992). The residuals are the differences between the fit of Eq. (1) and the data.

In Fig. A1 of Appendix A, the corresponding statistical significance of the responses to solar activity is plotted, and it can be seen that the statistical significance of the salient features of our results in Fig. 3 is generally well above the 2σ level.

However, this does not take into consideration the possibility of "aliasing", as follows. In linear least-squares regression, a core consideration is the curvature matrix, which needs to be inverted to obtain the error matrix and, subsequently, the desired expansion coefficients and their uncertainties (Bevington and Robinson, 1992). In the best of situations, the curvature matrix is diagonal, in which case the inverse is simply the inverse of the individual diagonal elements independently, and the values of the different matrix elements do not affect each other. This can be the case for orthogonal expansion functions, such as Fourier series, given certain conditions. This is not to say that for different situations, such as a fit to higher-degree polynomials, excellent results cannot be obtained.

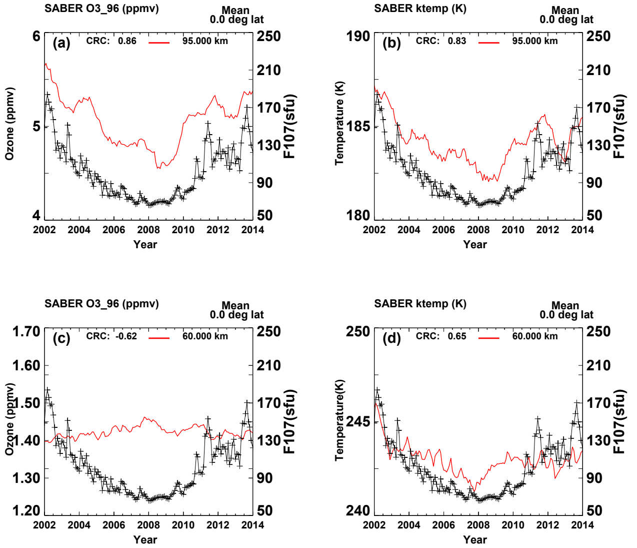

Figure 1. Top row: ozone zonal mean mixing ratios (left panel, red line) from mid-2002 to mid-2014, 95 km, 0° lat; right panel, as in left panel but for temperature. Lower row: as in top row but at 60 km. Black lines (+) show the corresponding monthly 10.7 cm flux (sfu) provided by NOAA.

When the curvature matrix is not diagonal, it may be that adding an extra term in the expansion series affects the values and uncertainties of the other coefficients. We use the term "aliasing" in this sense.

The algorithm (Eq. 1) that we use is basically the same as that used by most others, the various expansion functions are not orthogonal, and the off-diagonal elements of the curvature matrix can be significant. Although this is susceptible to the potential of aliasing, it is not necessary that there will be aliasing. In the present case, there could be a certain amount of aliasing in using Eq. (1), in particular between the linear trend term $a \times t$ and the solar response term $d \times \mathrm{F107}(t)$, since both are of low frequency over a solar cycle.

In data analysis, there are almost always uncertainties in the results, irrespective of aliasing. A problem with aliasing is that it can be difficult to estimate the degree of aliasing, or even if it exists.

One way of analyzing this is to try and estimate how much the uncertainties in the coefficients are potentially increased, in the case of aliasing. Tiao et al. (1990) and Weatherhead et al. (1998, 2000), among others, have used autoregressive (AR) processes as an additional term in the regression to study the effects of aliasing. Tiao et al. (1990) used a low-frequency AR process, so that it is “confounded” with the linear trend and the solar response terms, which can result in larger uncertainties in estimating these terms. Tiao et al. (1990) derive expressions such that their product with the magnitude of the data uncertainty provides an estimate of the uncertainty of the trend (and presumably the solar response). Their expressions are a function of the data length, and the trend uncertainty decreases as the data set length increases. The disadvantage of SABER data is that the data length is relatively short, covering little more than one solar cycle. Based on Tiao et al. (1990), for a data set of 11 years (somewhat shorter than the SABER data used), the increase in the uncertainty of the estimated trends is about a factor of 2. This should be applicable to the solar response term as well, since it is also of low frequency.

Another consideration is the variation of the solar flux itself. In Fig. 1, the black line (+) shows the variation of F107(t), the 10.7 cm solar flux, in solar flux units (sfu), from the middle of 2002 (near solar maximum, the middle of solar cycle 23) to the middle of 2014 (also near solar maximum, the middle of solar cycle 24). As can be seen, the end of cycle 23 (solar minimum) is near 2008–2009, with values of ∼ 70 sfu, and the end of the data (near solar maximum) has values about 140 sfu and decreases after that. The maximum of our data is at the beginning, and they have values ∼ 180 sfu, so for this cycle the solar activity has not recovered fully, reaching only ∼ 140 sfu. In fact, the shortfall is actually more, as the previous maximum is closer to 200 sfu, which occurred shortly before the beginning of Fig. 1. The maximum of the two previous cycles (21, 22) is also closer to 200 sfu, so the value of 140 sfu is anomalous. This, together with the relatively short time span of the data, increases the uncertainties of our estimates and should be kept in mind.

In the following, we will compare with results based on HALOE data, which also has a relatively short time span (1992–2004), but the solar flux during that period is not anomalous.

In principle, this increase in uncertainty would affect the interpretation of Fig. A1 in Appendix A. However, since not all physical variations are included in Eq. (1), it is likely that the sample variance that we use to stand for the data variance are overestimates of the data uncertainties and would then also overestimate the solar response uncertainties themselves, and we believe that the interpretation of Fig. A1 would hold even for possible increases of uncertainties. Although we do not do so here, if we take averages at the nine adjacent latitudes (±4°) and altitudes (±2.5 km), the uncertainties in the estimated responses can be further reduced by a factor of 3. The averaging would not affect the values of our responses significantly, because they are generally fairly smooth as a function of latitude and altitude, shown in Figs. 3 and A1.

In addition, we will test the quality of our results by comparing with previous results. As seen below, our correlations (phase relationships) between ozone and temperature

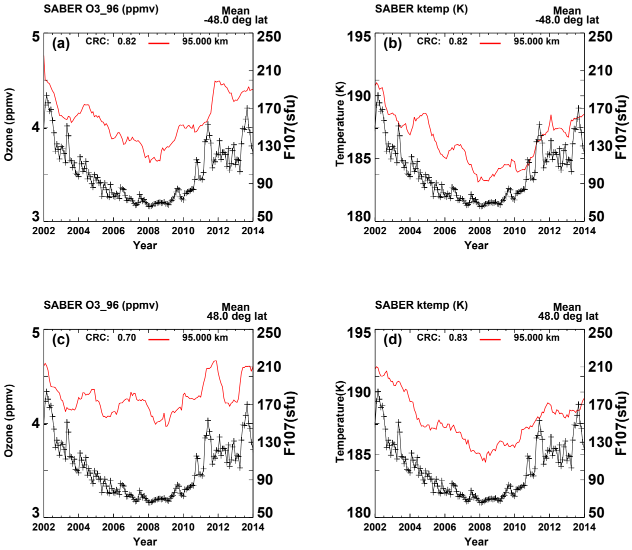

Figure 2. Top row: ozone zonal mean mixing ratios (left panel, red line) from mid-2002 to mid-2014, 95 km, 48° S lat; right panel, as in left panel but for temperature. Lower row: as in top row but at 48° N lat. Black lines (+) show the corresponding monthly 10.7 cm flux (sfu) provided by NOAA.

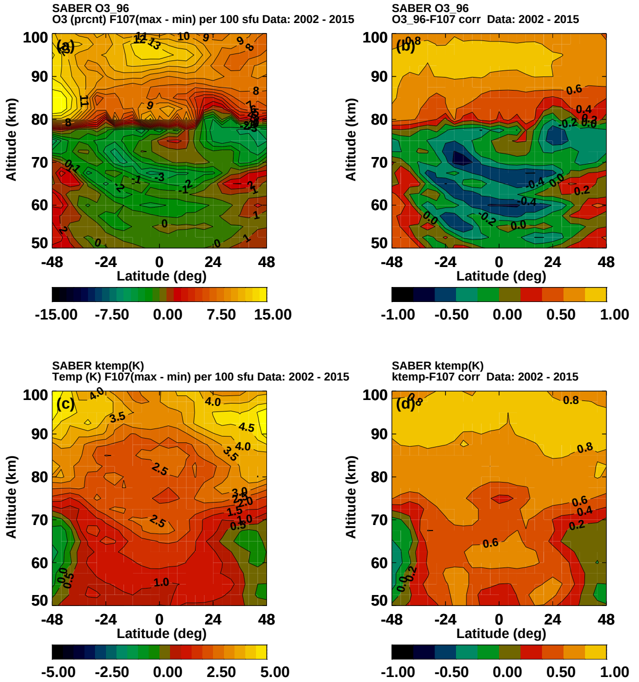

Figure 3. Ozone and temperature responses to solar variability on altitude (50 to 100 km) vs. latitude (48° S to 48° N) coordinates. Top row left: ozone responses at solar max−ozone responses at solar min, % (100 sfu)$^{-1}$. Right panel: correlation coefficients between ozone zonal means and 10.7 cm flux. Bottom row: as in top row but for temperature (K). Brown–green borders denote zero contours, with brown areas denoting positive trends.

responses to solar variability will also be a test of the quality of our results.

Nevertheless, it should be borne in mind that, in statistics, there can be isolated cases where results can be anomalous.

3 Results

We use the term "response" to solar activity generally to refer to the term $d \times$ F107 in Eq. (1), and specifically to ozone or temperature responses at solar maximum minus those at solar minimum, per 100 sfu. For ozone, it is also in terms of percentage differences. A positive response means that the response at solar maximum is larger than that at solar minimum.

In Fig. 1, the top left panel (a) shows our monthly zonal mean ozone (red lines) mixing ratios (part per million by volume, ppmv), at 95 km and the Equator, from the middle of 2002 to the middle of 2014, with seasonal and local time variations removed. Also shown are the corresponding 10.7 cm flux (black lines, right axis scale, units in sfu). The top right panel (b) corresponds to the left panel but for temperature (K).

In the top left (a) and right panels (b) of Fig. 1, it is evident that at 95 km both the ozone and temperature zonal means decrease from solar maximum to solar minimum (years 2002 to $\sim$ 2008). Therefore, the ozone and temperature responses at 95 km are both positive, decreasing with decreasing 10.7 cm flux. The ozone and temperature responses and solar activity are then all positively correlated (in phase) with each other.

The lower row of Fig. 1 corresponds to the upper row but for 60 km. In the lower left panel (c), for ozone at 60 km, it is evident that, unlike the case for 95 km, the ozone increases with decreasing solar activity from $\sim$ 2002 to 2008. At 60 km then, the ozone response to solar activity is negative (in contrast to that at 95 km). For temperature at 60 km, the lower right panel (d) of Fig. 1 shows that the temperature response remains positive, similar to that at 95 km.

At 60 km then, unlike the case for 95 km, the ozone and temperature responses are negatively correlated (out of phase) with each other.

In Fig. 1, the labels "CRC" denote the correlation coefficient between the data and the 10.7 cm flux. At 95 km and the Equator, the correlations with the 10.7 cm flux for ozone and temperature are $\sim$ 0.86 and 0.83, respectively. We think that the positive correlations are readily and visually discernible in the plots. At 60 km, the correlation coefficients with solar activity are ~ -0.62 for ozone and ~ 0.65 for temperature, and we think that both the negative and positive correlations are also discernible visually.

We will see in what follows that the behavior at 60 and 90 km follows a general and systematic pattern for the responses; namely, above $\sim$ 80 km, the ozone and temperature responses are positively correlated (in phase), while between 50 and $\sim$ 80 km they are negatively correlated (out of phase).

Importantly, this pattern is expected, as it is supported by previous studies, both empirical and theoretical.

These will be quantified, and for other altitudes and latitudes as well, in Sect. 3.1.

To examine further the behavior away from the Equator, the top row of Fig. 2 corresponds to the top row of Fig. 1 but at 48° S latitude, while the bottom row of Fig. 2 corresponds to 48° N latitude. It can be seen that at 95 km both the ozone and temperature responses remain positive at midlatitudes. We will see below that at altitudes above $\sim$ 80 km both the ozone and temperature responses remain positive for all latitudes in our region of study.

3.1 Responses of ozone and temperature to solar variability

As noted earlier, the term "response" to solar activity refers to ozone or temperature responses at solar maximum minus those at solar minimum, per 100 sfu. For ozone, percentage differences are used.

Here we quantify the discussion concerning Fig. 1, where it was seen that qualitatively the ozone and temperature responses at 60 and 95 km are discernible visually.

In Fig. 3, the left panels (a and c in upper and lower rows) show our ozone (percent) and temperature (K) responses to solar activity on altitude–latitude coordinates from 50 to 100 km, and 48 ° S to 48° N latitude. Positive values indicate that responses are larger near solar maximum relative to solar minimum, and they appear as brown, red, and yellow colors in Fig. 3. Negative responses are in green and blue colors. Because the responses are differences of values between solar maximum and solar minimum, the colors in Fig. 3 (left panels, a and c) themselves show whether the ozone and temperature responses are positively (in phase) or negatively (out of phase) correlated with each other.

3.1.1 Ozone

The left top panel (a) of Fig. 3 shows that, from $\sim$ 80 to 100 km, ozone responses to solar variability are positive for all latitudes and can exceed 10 % (100 sfu)$^{-1}$. From 50 to $\sim$ 80 km, the responses at low latitudes ($\sim \pm 35°$) are mostly negative (green colors) and can approach $\sim$ negative 3 % (100 sfu)$^{-1}$. In contrast, at midlatitudes in this region, the ozone responses are mostly positive and can approach $\sim$ 2 % (100 sfu)$^{-1}$. The upper right panel (b) of Fig. 3 corresponds to the left panel (a) but shows the correlation coefficients between the ozone zonal means themselves (see Fig. 1) and the 10.7 cm solar flux. It can be seen that, where the responses (left panel) are positive (negative), so are the correlations (right panel).

This is consistent with and quantifies our discussion in Fig. 1 at 95 and 60 km. It also supports our results of responses generally, because the correlations between ozone zonal means themselves (e.g., Fig. 1) and the 10.7 cm flux are independent of the regression (Eq. 1) used to obtain the responses in the left panels (a) and (c).

3.1.2 Temperature

The bottom row in Fig. 3 corresponds to the top row but for temperature. From ∼ 80 to 100 km, as in the case for ozone, temperature responses (lower left panel c) are positive for all latitudes and can approach ∼ 4 K $(100\,\mathrm{sfu})^{-1}$. From ∼ 50 to 80 km, the low-latitude responses remain positive, with values up to ∼ 2.5 K $(100\,\mathrm{sfu})^{-1}$, but are weakly negative at midlatitudes.

3.1.3 Ozone–temperature correlation and phase relations

Figure 3 shows that the correlation and phase relations of ozone and temperature responses follow systematic and robust patterns over the range of altitudes and latitudes under consideration. From ∼ 80 to 100 km, it is seen that the ozone (left panel a, top row) and temperature (left panel c, lower row) responses are both positive (red, yellow) for all latitudes, and they are then positively correlated (in phase) with each other for all latitudes in this region.

In contrast, between ∼ 50 and 80 km, both the ozone responses (upper left panel a) and temperature responses (lower left panel c) can be positive (red, yellow) or negative (green), depending on the altitude and latitude. At low latitudes (within ∼ 35° of the Equator), from ∼ 50 to 80 km, the ozone responses have become mostly negative (green), but the temperature responses have remained positive (red, yellow) as in the lower thermosphere. At midlatitudes (poleward of ∼ 35°), from 50 to 70 km, the ozone responses are mostly positive (brown, red). In contrast, the temperature responses at midlatitudes are mostly negative (green).

Consequently, throughout the mesosphere, between 50 and 80 km, the ozone and temperature responses are essentially negatively correlated (out of phase) with each other for all latitudes.

These ozone–temperature relationships are as expected, as discussed further in the next section.

3.2 Correlations between ozone and temperature with each other

Previous studies of ozone–temperature variations show that the correlations and phase relationships between ozone and temperature responses of our results, as described above, can be expected.

For variations over days and longer, Barnett et al. (1975) have shown that the dependence of photochemical reaction rates on temperature, by themselves (excluding dynamics), would lead in the upper stratosphere and in the mesosphere to negative correlations (out of phase) between temperature and ozone variations. Quantitatively, this would depend on the details of the ozone–temperature feedback loop that is set up. Finger et al. (1995) found that ozone and temperature variations are positively correlated (correlation coefficient) in the lower stratosphere and negatively correlated in the upper stratosphere, based on nearly 2 decades of satellite measurements. Finger et al. (1995) also use the correlation between ozone and temperature as a “sniff” test on different and new measurements.

Brasseur and Solomon (2005) have noted that between ∼ 30 and ∼ 75 km photochemistry is dominant, leading to negative ozone–temperature correlations (see their Fig. 5.11, or Fig. 11 of Garcia and Solomon, 1985). Below ∼ 25 km and above ∼ 85 km, photochemistry no longer dominates. There are transition regions near 25–30 and 75–85 km, which are also somewhat latitude dependent. It should be noted, however, that Rood and Douglass (1985) and Douglass et al. (1985) show that dynamics can at times also cause anticorrelations between temperature and ozone, so there can be exceptions.

As described above in Sect. 3.1 and seen in Fig. 3, our responses fit very well with these previous findings.

Although not shown, in the upper stratosphere and tropics, our ozone and temperature responses are also mostly negatively correlated (out of phase) and continue to fit in with these expected correlations and phase relationships. In this region, our correlations are mostly negative because our ozone responses have become mostly positive, while the temperature responses have become mostly negative. However, we should note that there have been other previous studies that support the opposite view, with both ozone and temperature responses being positive (e.g., Austin et al., 2008; Gray et al., 2009). Past studies which agree with our view that the temperature responses are negative include those by Fadnavais and Beig (2006), Hood (2004), and Brasseur (1993).

In our analysis (Huang et al., 2008a) of ozone and temperature QBOs and SAOs, and trends (Huang et al., 2014), all also based on SABER data, we have found that the corresponding ozone–temperature correlations for these components also agree with this view. This is also consistent with results based on measurements from the Microwave Limb Sounder (MLS) on UARS, as described in Huang et al. (2008a).

The probability that these expected correlations are accidental or fortuitous is very small. Therefore, the comparisons provide confidence for our findings of ozone and temperature responses.

3.3 Correlations of ozone and temperature responses with solar flux

To reiterate, in the right panels of Fig. 3, the correlation coefficients between the ozone zonal means and the 10.7 cm flux mirror the ozone and temperature responses (left panels) very well. This lends clear support to the validity of our analysis, because the correlations are obtained independently of the multiple regressions (Eq. 1) used.

4 Comparisons

Previous empirical studies have been based on satellite, ground-based, and rocketsonde data. Operational satellites provide global coverage, spanning decades. However, their altitude coverage is limited to the stratosphere. In the mesosphere, besides SABER, measurements from HALOE on UARS cover most of the altitude coverage of SABER.

4.1 Comparisons with other measurements and analysis

4.1.1 Ozone

Figure 4 shows our results (black lines) at the Equator as a function of altitude, from 50 to 100 km. The left plot (a) is for ozone and the right plot (b) is for temperature.

Also plotted in Fig. 4 are results by Beig et al. (2012), based on HALOE data, denoted by the blue (diamonds, BEIGS) for 0–30° S latitude and green (asterisks, BEIGN) for 0–30° N latitude. We manually transferred their results to Fig. 4, so they are not exact but should be adequate for purposes here. HALOE is a solar occultation measurement, and data are made at spacecraft sunset and sunrise only, throughout the mission. Beig et al. (2012) point out that the responses to solar activity can depend significantly on whether the values are made at sunrise or sunset. For example (not shown), near 0.02 hPa (∼ 76 km), the sunset responses are near zero, while for sunrise the responses are ∼ negative 10 % (100 sfu)$^{-1}$. Near 0.003 hPa (∼ 87 km), their sunset responses are positive, ∼ 15 % (100 sfu)$^{-1}$, and are near zero for sunrise. They therefore use averages between values at sunset and sunrise for comparison.

As noted earlier, our zonal means are averages over both longitude and local time in a consistent manner. This is consistent with the zonal averages of 3-D models (Austin et al., 2008). With these differences in mind, the ozone results of Beig et al. (2012) based on HALOE data compare favorably with our results. In Fig. 4, left panel for ozone, between 50 and ∼ 75 km, both Beig et al. (2012) and our ozone responses are either ∼ 0 or negative. Between ∼ 70 and 85 km, we both show rapid increases with altitude, with the ozone responses varying from negative values to positive local maxima just below 85 km.

Some models also predict negative ozone responses between 50 and 80 km, although their magnitudes can differ. Beig et al. (2012) show corresponding results at the Equator from the 3-D chemistry–climate Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA), which show hints of negative ozone responses between 65 and 75 km, and steady values of ∼ 5 % (100 sfu)$^{-1}$ between 80 and 95 km. The 2-D models of Brasseur (1993) and Fleming et al. (1995) show larger negative ozone responses in the mesosphere and attribute the negative values to temperature–ozone feedback.

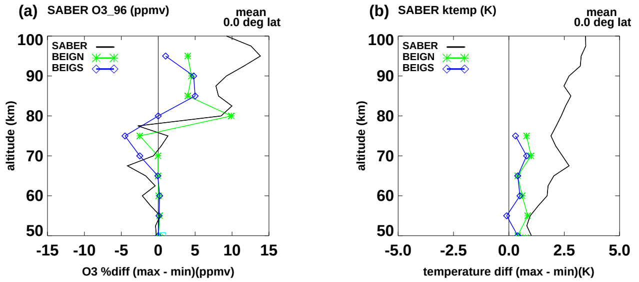

Figure 4. Ozone (left panel) and temperature (right panel) responses to solar activity vs. altitude, from 50 to 100 km. Values are responses at solar max−responses at solar min in % (100 sfu)$^{-1}$ for ozone and K (100 sfu)$^{-1}$ for temperature. Black lines denote SABER responses at Equator. Green asterisks denote responses based on HALOE by Beig et al. (2012) for 0–30° N (BEIGN). Blue diamonds denote Beig et al. (2012) for 0–30° S (BEIGS).

4.1.2 Temperature

The right panel (b) of Fig. 4 corresponds to the left panel (a) but for temperature. Beig et al. (2012) and our responses track each other reasonably, although our temperature responses are larger. As with the case for ozone, Beig et al. (2012) and our results agree reasonably, considering that their results are an average of sunrise and sunset, and are over 30° latitude bands, while our zonal means are results are at the Equator, averaged over the range of local time and longitude in a consistent manner.

Their temperature responses, like ours, are positive, so between ∼ 50 and 75 km the ozone and temperature responses are negatively (out of phase) correlated. This conforms to our expectations, discussed earlier in Sect. 3.2, that between 50 and ∼ 80 km the ozone and temperature responses are expected to be negatively correlated (out of phase), while above ∼ 80 km they are positively correlated (in phase).

Remsberg (2009) also estimated the temperature responses (but not ozone), based on HALOE data, from 43 to 80 km and 40° S to 40° N latitude. However, he used a different approach, by fitting a sinusoid with a period of 11 years to get an estimate of the temperature response, and then adjusting the results in order to compare with results that do not assume a single 11-year response. Although not shown, there are similarities with our results, such as the 1 K contour near 48 km and the Equator. However, our values continue to grow with altitude, while the results of Remsberg (2009) approach negative values at the Equator near 75 km. In any event, as with Beig et al. (2012), his results do not extend past 80 km, so we cannot compare with our results with HALOE at higher altitudes.

The dependence of the responses on local time noted by Beig et al. (2012) presents caveats in making direct comparison with measurements from ground-based and rocketsonde data. It is not clear how these measurements relate to variations with local time and zonal means. So we will only briefly describe a couple of comparisons.

For higher altitudes of 80–100 km, the temperature responses found by She and Krueger (2004) and She et al. (2009), based on lidar measurements over Fort Collins, CO (41° N 105° W, for 11 and 18 years, respectively, beginning ∼ 1990), compare favorably with ours in their relative variations, especially considering that they are nocturnal measurements at a specific longitude, over different time spans. Near 100 km, their values are ∼ 0.05 K sfu^{-1}, showing small changes with altitude, reaching values slightly larger than 0.05 K sfu^{-1} near 95 km and decreasing back to ∼ 0.05 K sfu^{-1} at 85 km. As can be seen in Fig. 3 (bottom left panel), our responses near 40° N and 100 km are ∼ 4 K $(100\,\text{sfu})^{-1}$, with values approaching 5.0 $(100\,\text{sfu})^{-1}$ at ∼ 95 km and decreasing to ∼ 4 K $(100\,\text{sfu})^{-1}$ at 80 km.

Keckhut et al. (2005) give responses of temperature, based on rocketsonde measurements in three latitude bands. In the tropics (∼ 8° N latitude) and subtropics (22–34° N latitude), the responses can approach ∼ 2 K between 50 and 70 km, but unlike our results they begin to decrease at higher altitudes.

4.2 Comparison with previous SABER analysis

As noted earlier, Nath and Sridharan (2014) have derived responses to solar variability, also based on SABER data, but only at 10–15° latitude. Comparisons should help in analyzing the quality of the results.

Figure 5 shows our results for ozone (left plot a) and temperature (right plot b), at 12° latitude (black line), along with results of Nath and Sridharan (2014), red line, at 10–15° latitude band, from 20 to 100 km. We manually transferred the Nath and Sridharan (2014) results to Fig. 5, so they are not exact but should be adequate for purposes here.

In the left plot (a) of Fig. 5, from 20 to 50 km, our ozone results agree very well with those of Nath and Sridharan (2014), especially considering that their analysis covers 10 to 15° latitude, while our responses are for 12° latitude. From 50 to 80 km, the agreement still appears to be good, both with near-zero values. However, a caveat is that in this region the ozone mixing ratios are relatively very small, so on the scale plotted, variations and differences would not show up well, because they are not plotted as percent differences, as in previous figures, but in units of ppmv. The choice of units is to conform with Nath and Sridharan (2014). Above ∼ 80 km, our responses are systematically smaller. An explanation for these differences is given next in comparing temperature responses.

For temperature, as seen in the right plot (b) of Fig. 5, our temperature responses, as for those of ozone, again agree very well up to ∼ 45km with those of Nath and Sridharan (2014), but not so well from ∼ 45 to 100 km.

We believe that the differences between our results and those by Nath and Sridharan (2014), especially at higher altitudes for both ozone and temperature, are due to the local time variations that are in the SABER data, as discussed in Sect. 2.1 (Data characteristics).

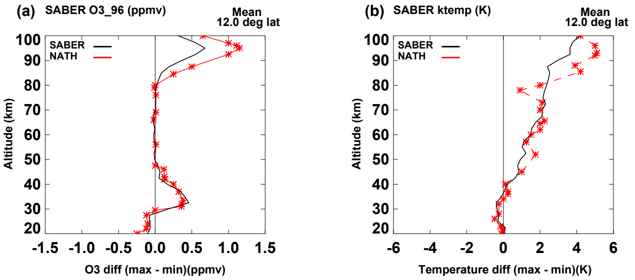

Figure 5. Ozone (left) and temperature (right) responses to solar activity vs. altitude, from 20 to 100 km. Values are responses at solar max−responses at solar min in ppmv $(100\,\text{sfu})^{-1}$ for ozone and K $(100\,\text{sfu})^{-1}$ for temperature. Black lines denote SABER responses at 12° lat; red color denotes results of Nath and Sridharan (2014), for 10–15° lat, also based on SABER data.

Nath and Sridharan (2014) note that they use “monthly averaged zonal mean” for ozone and temperature. So it does not appear that they have considered variations with local time (diurnal variations, tides) in their regression analysis. For both ozone and temperature, diurnal variations are relatively small below ∼ 40 km but can be the dominant form of variations in the mesosphere and lower thermosphere (see Zhang et al. (2006), Mukhtarov et al. (2009), and Huang et al. (2010a) for temperature and Huang et al. (2008b, 2010b) for ozone). Even in the stratosphere, variations with local time may not be negligible.

5 Summary and discussion

We have derived new ozone and temperature responses to the sun’s 11-year cycle, based on measurements from SABER, something that has not been available previously on a global scale, up to 100 km. The simultaneous measurements of ozone and temperature allow for studying details of correlations and phase relationships between them, which provide important information and support the quality of our results. In addition to extending global altitude coverage of previous measurements, SABER data provide 2.5 km resolution in altitude and 4° resolution in latitude from 2002 to 2014.

As discussed in Sect. 2.2.2, a longer time span of the data would help in reducing the uncertainties. The SABER instrument has now made measurements with essentially no data gaps since the beginning of 2002, and it would a significant advantage if this could continue for at least several more years.

5.1 Results

From ∼ 80 to 100 km, the responses are larger for both ozone and temperature than at lower altitudes, and both are uniformly positive for all latitudes. In this region, the amplitudes can exceed $\sim 10\,\%\,(100\,\mathrm{sfu})^{-1}$ for ozone and $\sim 4\,\mathrm{K}\,(100\,\mathrm{sfu})^{-1}$ for temperature. From ∼ 50 to 80 km, both ozone and temperature responses can be positive or negative, depending on location. The ozone responses are mostly negative at low latitudes (∼ ±35°) but are mostly positive at midlatitudes. In contrast, the temperature responses have opposite signs, being generally positive at low latitudes and weakly negative at midlatitudes, as seen in Fig. 3. The ozone and temperature responses are then uniformly negatively correlated (out of phase) with each other in the mesosphere, for all latitudes.

Qualitatively, the signs and magnitudes of the responses at 95 and 60 km can clearly be discerned in Fig. 1, independent of the regression analysis. This lends confidence to our results.

The correlations in the different altitude ranges are consistent with previous studies (e.g., Brasseur and Solomon, 2005; Garcia and Solomon 1986) which show that above ∼ 80 km the ozone and temperature variations (although not specifically the responses) are expected to be positively correlated (in phase) due to the dominance of dynamics in this region. Between ∼ 30 and 75 km, the correlations are expected to be negatively correlated (out of phase) because photochemistry is more in control (Barnett et al., 1975; Finger et al., 1995; Brasseur and Solomon, 2005).

Although not shown, our results from ∼ 30 to 50 km also fit in with these correlations and phase relationships.

This is also consistent with our results concerning ozone and temperature QBOs and SAOs (Huang et al., 2008a), and trends (Huang et al., 2014), also based on SABER data, and with results based on measurements from the MLS on UARS (Huang et al. 2008a).

In all regions in this study, the correlation coefficients between the ozone zonal means themselves (e.g., in Fig. 1) and the 10.7 cm solar flux show that where the responses to solar variability are positive (negative) the corresponding correlation coefficients are also positive (negative), as seen in Fig. 3. This further supports our results because the correlations are independent of the responses found by our multiple regression.

The probability that all the agreements are fortuitous or coincidental is very low.

5.2 Comparisons

Considering the different conditions described above, our results compare well with those of Beig et al. (2012), based on HALOE measurements. At low latitudes, theirs and our ozone and temperature responses track each other reasonably as a function of altitude, although our temperature responses are larger. Significantly, the positive and negative correlations from Beig et al. (2012) are consistent with ours.

We have also compared results with those of Nath and Sridharan (2014), whose analysis is also based on SABER data. Our results for both ozone and temperature agree very well in the stratosphere, as seen in Fig. 5. As discussed in Sect. 4.2 (comparison with previous SABER analysis), with increasing altitude into the mesosphere and lower thermosphere, the agreement becomes less good. We believe that the differences are because Nath and Sridharan (2014) do not appear to have accounted for diurnal variations in the SABER data (see Sect. 2.1), which is not generally part of other satellite measurements. With increasing altitude from ∼ 45 km, the diurnal variations increase and can be dominant at higher altitudes for both ozone and temperature. The excellent agreement in the stratosphere (Fig. 5) supports the validity of our results.

In Sect. 2.2.2, we noted that in Eq. (1) there could be some aliasing between the linear trend term and the solar response term. A particular aspect of aliasing is that it is difficult to estimate exactly the degree of its effects, which can be negligible to significant. Previous studies estimated effects of aliasing in terms of increased uncertainties, and we should be mindful of such effects, if any. For example, as seen in Fig. 3 (lower left), which shows our derived temperature responses, there is a small region of local maximum at the Equator near 70 km. In Huang et al. (2014), we had also estimated corresponding linear trends (not shown), also based on SABER data. There is a similar region of local maximum (in magnitude, neglecting the sign), thereby indicating the possibility of aliasing between the trend and solar terms in Eq. (1). As discussed earlier in reference to Fig. 1 (lower right panel), which shows the temperature zonal means at 60 km and the Equator, the decrease of the temperature from ∼ 2002 to 2008 is clearly discernible in the data themselves and is consistent with the derived temperature responses to solar activity seen in Fig. 3 (lower left panel). We have also generated plots (not shown) corresponding to Fig. 1 (lower right panel) but at 65 and 70 km, and they show that the temperature decreases from 2002 to 2008 are also clearly evident, as in the case at 60 km. In addition, the magnitude of the decreases is seen to be somewhat larger than that at 60 km, by about the amount needed to be consistent with the derived responses in Fig. 3 (lower left panel). This indicates that qualitatively our temperature responses between 60 and 70 are realistic and are not an artifact of the analysis, and that aliasing is not a significant problem.

Appendix A: Statistical significance of responses

As noted above, a commonly used criterion to indicate if an estimated response to solar variability is statistically significant is that its magnitude be greater than 2σ (∼ 95% confidence level), where σ is the uncertainty of the estimate of the responses. In Fig. A1, the right plots (b and d, top and bottom row) show the ratios of the responses to their respective uncertainties for ozone and temperature, respectively, on altitude–latitude coordinates. The left plots (a and c) correspond to the right plots but show the corresponding responses themselves, as in Fig. 3 of the manuscript. In the right-hand plots (b and d) of Fig. A1, the brown colors correspond to a value of 2 for the ratios of the magnitude of the responses to their respective uncertainties, σ, and mark the level of statistical significance. The red and yellow colors in the right-hand plots correspond to situations that are statistically significant (greater than 2), while the green colors correspond to ratios of less than 2. The brighter yellow colors are a result of the ratios beings larger than the upper plot limit. The lower plot limit is set to negative so that the brown color demarks the significance of the results. As noted earlier, we can increase the confidence level of our results by averaging. Although we do not do so here, if we take averages at adjacent latitudes (±4°) and altitudes (±2.5 km), the uncertainties in the estimated responses can be further reduced by a factor of 3. The averaging would not affect the values of our responses significantly, because they are fairly smooth as a function of latitude and altitude, shown in the left panels of Fig. A1.

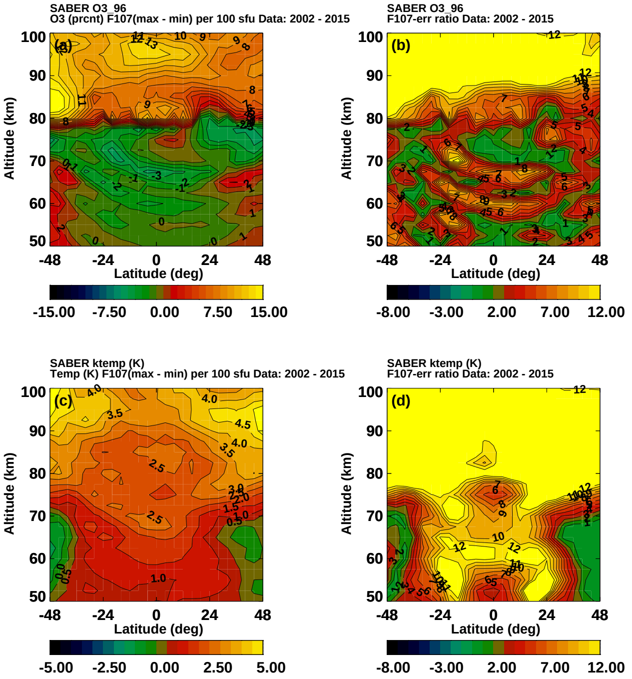

Figure A1. Top row: ozone solar responses (top left) and ratios to their respective uncertainties (top right). Bottom row: corresponds to top row but for temperatures. The brown colors separate those within the 95 % confidence (2σ, red, yellow) from others (green).

Data availability

The SABER data are freely available from the SABER project at http://saber.gats-inc.com/.

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